AD-A107 935 NAVAL COASTAL SYSTEMS CENTER PANAMA CITY FL F/G 9/1
IMPEDANCE MATCHING FOR LONG CABLES CARRYING ULTRASONIC SIGNALS.(U)
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TECHNICAL MEMORANDUM
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OCTOBER 1981

IMPEDANCE MATCHING FOR LONG CABLES CARRYING ULTRASONIC SIGNALS

JOHN MITTLEMAN

NAVAL COASTAL SYSTEMS CENTER
NCSC
PANAMA CITY, FLORIDA 32407

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER TM 325-81	2. GOVT ACCESSION NO. AD-A107 935	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Impedance Matching for Long Cables Carrying Ultrasonic Signals		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) John Mittleman		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Coastal Systems Center Panama City, FL 32407		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Task WR02574
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE October 1981 13. NUMBER OF PAGES 25
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Cables; Impedance Matching; Ultrasonics; Transducers; Testing; Transmission Lines; Signals

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Long coaxial cables, when used for ultrasonic inspection, have been known to produce extraneous signals and attenuate valid signals. In this report, the theory of transmission lines is applied to such cables and is shown to predict the unwanted phenomena. The theory is then applied to the design of matching networks composed of one resistive and one inductive component. A series R-L network placed in parallel with the transducer is shown to produce a satisfactory impedance match, and its performance is demonstrated through

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20. ABSTRACT (continued):

experiments on a 1000-foot length of coaxial cable terminated by the network and an ultrasonic transducer.

LIST OF SYMBOLS

A	Attenuation constant for a known cable length (dB)
B	Phase constant for a known cable length (degrees)
C	Capacitance (Farads)
E	Voltage (volts)
E_L	Voltage at the load (receiving) end
E_s	Voltage at the generator (sending) end
F	Frequency (Megahertz)
I	Current (Amperes)
I_L	Current at the load end
I_s	Current at the sending end
L	Inductance (Henries)
R	Resistance (ohms)
Z	Impedance (complex), (ohms)
Z_o	Characteristic impedance
Z_g	Source (generator) output impedance
Z_L	Load input impedance
Z_s	Cable input impedance at the sending end
Z_s (short)	Z_s with the load end short circuited
Z_s (open)	Z_s with the load end open circuited
Z_{sc}	Z_s (short)
c	Speed of light in a vacuum ($\simeq 3 \times 10^8 \frac{m}{sec}$)
e	Base of natural logarithms (2.718. . .)
j	$\sqrt{-1}$
ℓ	Cable length (feet or metres)

v	Speed of electromagnetic wave propagation in a material
α	Attentuation constant ($\frac{\text{dB}}{\text{1000 feet}}$ or $\frac{\text{nepers}}{\text{metre}}$)
β	Phase constant ($\frac{\text{degrees}}{\text{1000 feet}}$ or $\frac{\text{radians}}{\text{metre}}$)
γ	Propagation constant ($\alpha + j\beta$)
π	Pi (3.141. . .)
τ	Time (seconds)
ω	Angular frequency ($\frac{\text{radians}}{\text{second}}$)

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BACKGROUND

Underwater ultrasonic testing at the Naval Coastal Systems Center (NCSC) is performed by a team composed of a diver and a topside technician. Sufficient transducer cable is used so that all test hardware remains out of water, except the transducer.

Unfortunately, the long transducer cable acts as an electrical network for which neither the ultrasonic pulser/receiver nor the transducer was designed, so the quality of ultrasonic signals is often degraded. At first, it was thought that amplification of the signals generated by the transducer would restore the signal quality; but it was later realized that the fundamental problem is created by impedance mismatches which foster reflections and decrease power transmitted to and from the transducer.

During 1980 efforts to increase the usable transducer cable length centered around impedance matching network design.

BASIC EQUATIONS

In our impedance matching design work, the following basic equations which relate electrical conditions at the ends of a transmission cable were used:[1]

$$E_s = (E_L + I_L Z_o)\,(e^{\gamma\ell})/2 + (E_L - I_L Z_o)\,(e^{-\gamma\ell})/2$$

and

$$I_s = (E_L + I_L Z_o)\,(e^{\gamma\ell})/2Z_o - (E_L - I_L Z_o)\,(e^{-\gamma\ell})/2Z_o$$

where E_s and I_s are voltage and current at the sending end

E_L and I_L are voltage and current at the receiving end

---

[1]Karakash, John J., "Transmission Lines and Filter Networks," MacMillan Co., 1950.

Z_o is the cable's characteristic impedance

γ is a propagation constant and

ℓ is the cable length

Note that for an infinitely long cable (in which there is no reflected wave) the term $e^{-\gamma\ell}$ drops out and the sending end impedance is the characteristic impedance, Z_o.

$$Z_s \text{ (for } \ell = \infty) = \frac{E_s}{I_s} \text{ (for } \ell = \infty) = Z_o \quad .$$

Also note that the equations are reminiscent of hyperbolic functions; in fact, for the load end open circuited or short circuited the input impedances are

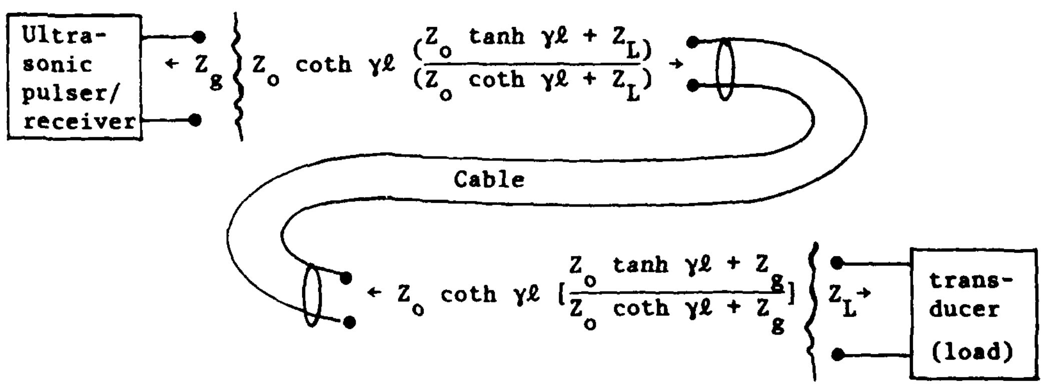
$$Z_s \text{ (open circuit at load end)} = Z_o \coth \gamma\ell$$

or $$Z_s \text{ (short circuit at load end)} = Z_o \tanh \gamma\ell \quad .$$

For any other load impedance the input impedance can be expressed as

$$Z_s \text{ (for } Z_L \text{ at load end)} = Z_s \text{ (open)} \frac{(Z_s \text{ (short)} + Z_L)}{(Z_s \text{ (open)} + Z_L)} \quad .$$

Looking from the load end toward the pulser/receiver (which has an internal impedance of Z_g) the equations can be written in much the same fashion. This leads to the following configuration:



The possibilities for mismatched impedances are numerous. Inefficient power transfers and troublesome reflections can occur at both cable ends unless impedances are properly matched. This is not easy since the load impedance (the transducer's impedance) varies as a function of frequency. The term "matching" is somewhat deceiving in that it does not mean equating the impedances looking up and down the cable from any given point. Rather, it means making the impedance looking either direction from any point on the cable equal to the cable's characteristic impedance. Though this is a more restrictive requirement than having equal impedances looking in both directions, it is not as bad as first thought because if both ends are terminated in a device having an input impedance equal to the characteristic impedance ($Z_g = Z_L = Z_o$) then the input impedance of the terminated cable becomes:

$$Z_s = Z_o \coth \gamma \ell \left[\frac{Z_o \tanh \gamma \ell + Z_o}{Z_o \coth \gamma \ell + Z_o}\right] = Z_o$$

showing that cable length and the propagation constant drop out of the expression.

To predict performance if Z_L or Z_g is not equal to Z_o the variables seen in the preceding expressions; namely, Z_o, $\gamma\ell$, Z_g, and Z_L must be quantified. The following discussions pertain to this quantification.

CABLE PARAMETERS

Cable parameters are, at best, difficult to measure, and manufacturer's information is often available at only a few selected frequencies. However, with modern electronic impedance measuring instruments the task is tractable.

Let us consider what measurements would be of use. Knowing that $Z_{sc} = Z_o \tanh \gamma\ell$ (where Z_{sc} indicates the cable's input impedance with the load end short circuited) allows calculation of the magnitude (or phase) of the cable's input impedance when the cable is short circuited if Z_o (the characteristic impedance), γ (the propagation constant), and ℓ (the cable length) are known. Alternatively, measurements can be taken and calculations made to determine the unknown constants. For instance, if the magnitude of Z_{sc} (denoted $\|Z_{sc}\|$) and the angle of Z_{sc} (denoted $\measuredangle Z_{sc}$) are measured then $\gamma\ell$ and Z_o can be determined as follows:

$$Z_{sc} = Z_o \tanh \gamma\ell$$

$$\|Z_{sc}\| = \|Z_o\| \ \|\tanh \gamma\ell\|$$

and $$\measuredangle Z_{sc} = \measuredangle Z_o + \measuredangle \tanh \gamma\ell$$

Since $\gamma\ell$ may be complex, let us substitute A + jB for $\gamma\ell$.

Then $$\|Z_{sc}\| = \|Z_o\| \ \|\tanh (A + jB)\|$$

By straightforward algebraic manipulation we find

$$\tanh (A+jB) = \frac{e^{A+jB} - e^{-(A+jB)}}{e^{A+jB} + e^{-(A+jB)}}$$

reduces to

$$\tanh (A+jB) = \frac{e^{2A} - e^{-2A} + 2j \sin 2B}{e^{2A} + e^{-2A} + 2 \cos 2B}$$

from which

$$\|\tanh (A+jB)\| = \frac{(e^{4A} + e^{-4A} - 2 \cos 4B)^{\frac{1}{2}}}{(e^{2A} + e^{-2A} + 2 \cos 2B)} .$$

Note that $A = \alpha\ell$ (the attenuation constant) and $B = \beta\ell$ (the phase constant) can be expected to be smoothly increasing functions of frequency. Thus, periodicity in $\|\tanh \gamma\ell\|$, (or, since $\|Z_o\|$ is also expected to be a slowly varying function of frequency, periodicity in $\|Z_{sc}\|$) is attributable to the periodic nature of cos 2B and cos 4B, and will produce local extrema when 2B is approximately equal to a multiple of π (180°). When this is the case,

$$\|Z_{sc}\| \simeq \|Z_o\| \ \left(\frac{(e^{4A} + e^{-4A} \mp 2)^{\frac{1}{2}}}{e^{2A} + e^{-2A} \pm 2}\right)$$

which reduces to

$$\|Z_{sc}\| = \|Z_o\| \ \tanh A \text{ (at local minima)}$$

or

$$\|Z_{sc}\| = \|Z_o\| \coth A \text{ (at local maxima)} \quad .$$

With these two equations in hand we are ready to use measurements of Z_{sc} since we now know that (at least approximately)

a. The upper envelope of $\|Z_{sc}\|$ is $\|Z_o\|$ coth A.

b. The lower envelope of $\|Z_{sc}\|$ is $\|Z_o\|$ tanh A.

c. Local maxima of $\|Z_{sc}\|$ occur at B equal to odd multiples of $\pi/2$.

d. Local minima of $\|Z_{sc}\|$ occur at B equal to even multiples of $\pi/2$.

For A, B, and Z_o varying smoothly as functions of frequency, interpolation between extrema can be used to find

$$\|Z_o\| = \left(\|Z_{sc}\|_{\substack{\text{upper}\\ \text{envelope}}} \; \|Z_{sc}\|_{\substack{\text{lower}\\ \text{envelope}}} \right)^{\frac{1}{2}}$$

and $\tanh A = \left(\|Z_{sc}\|_{\substack{\text{upper}\\ \text{envelope}}} \Big/ \|Z_{sc}\|_{\substack{\text{lower}\\ \text{envelope}}} \right)^{\frac{1}{2}}$

from which A can be calculated

$$A = \frac{1}{2}\ln\left(\frac{1 + \tanh A}{1 - \tanh A}\right) \quad .$$

The extrema themselves are used to plot B as a function of frequency since extrema occur at $B \simeq n\pi/2$.

This procedure was applied to measurements taken on 1000 feet of RG-58 coaxial cable. Impedance measurements were made every 0.02 MHz from 0.5 MHz to 6.48 MHz using the instrumentation shown schematically in Figure 1. These impedance values (Figure 2) were the basis for calculations leading to values of $\|Z_o\|$, A, and B shown in Figures 3, 4, and 5. Curve fitting yielded the following expressions which, while approximate, serve well for calculations:

$$Z_o \simeq 50\Omega$$

$$A \simeq (4.8\sqrt{F} - 1.4) \text{ dB}$$

$$B \simeq 564F \text{ degrees}$$

where F is frequency, in megahertz.

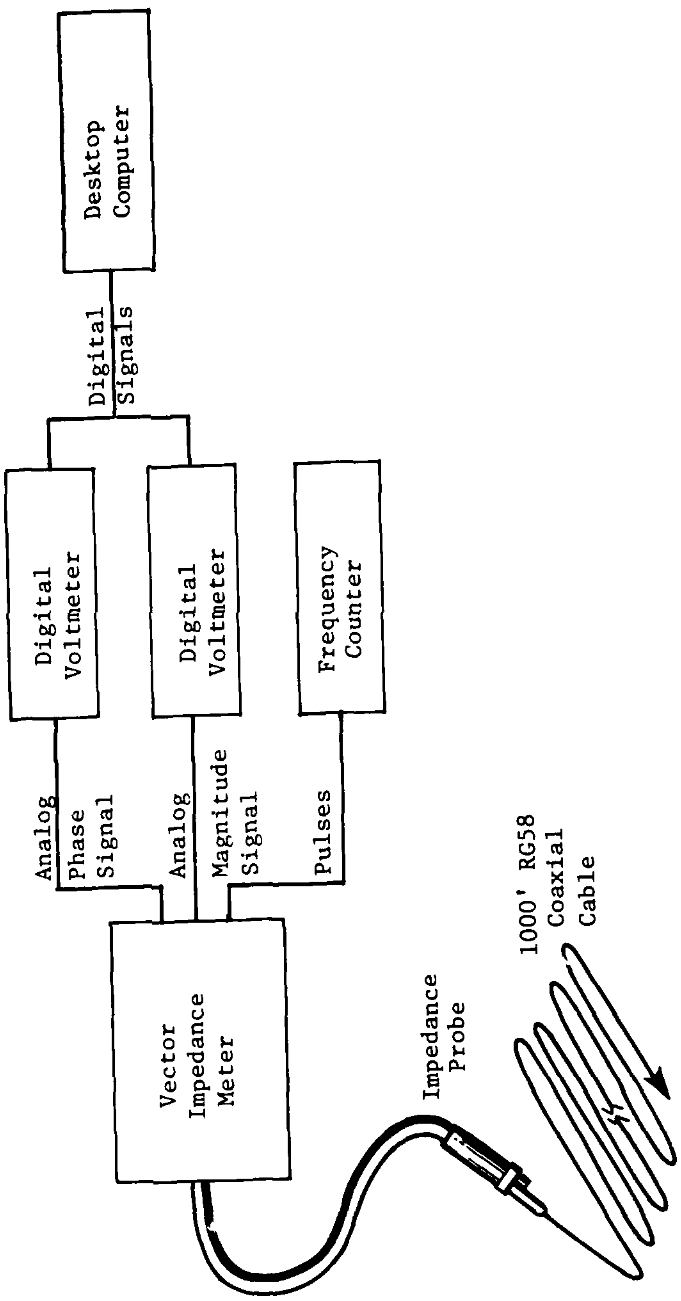


FIGURE 1. INSTRUMENTATION FOR CABLE PARAMETER MEASUREMENTS

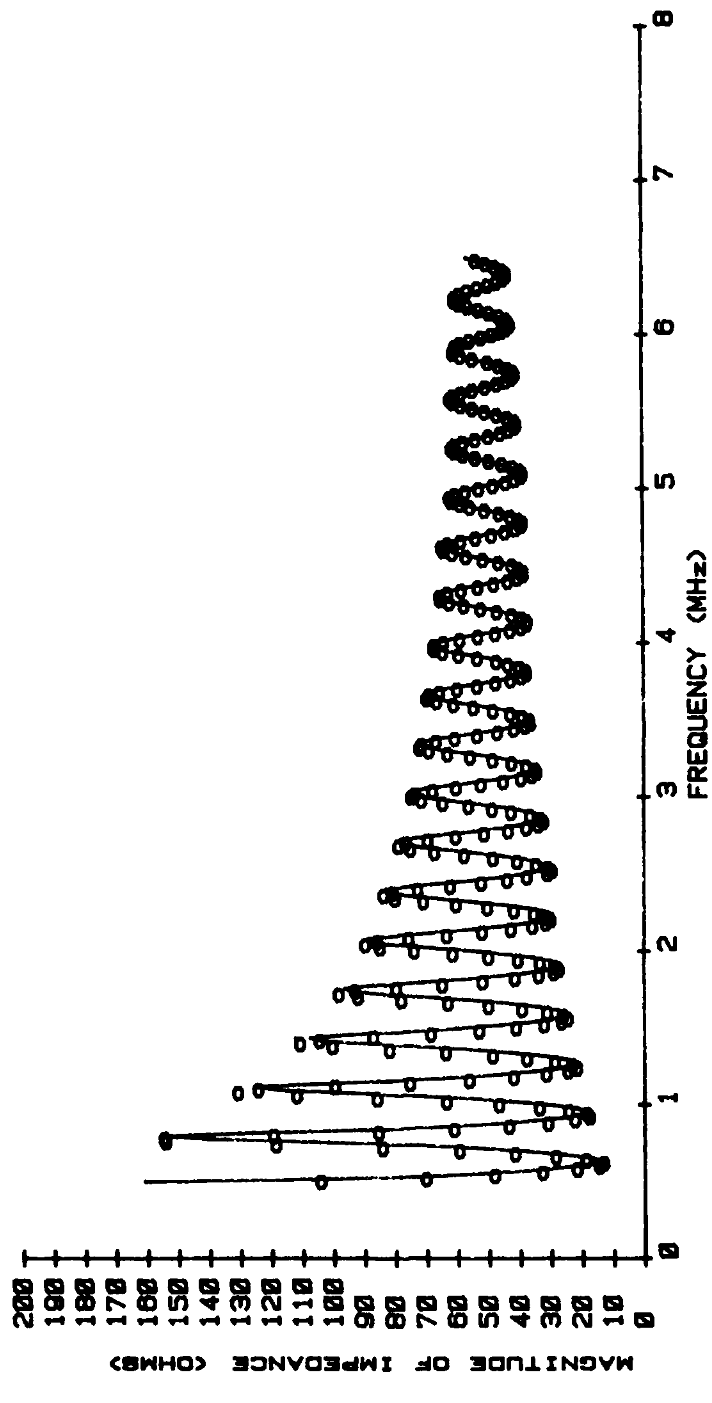


FIGURE 2. CABLE IMPEDANCE (MAGNITUDE)

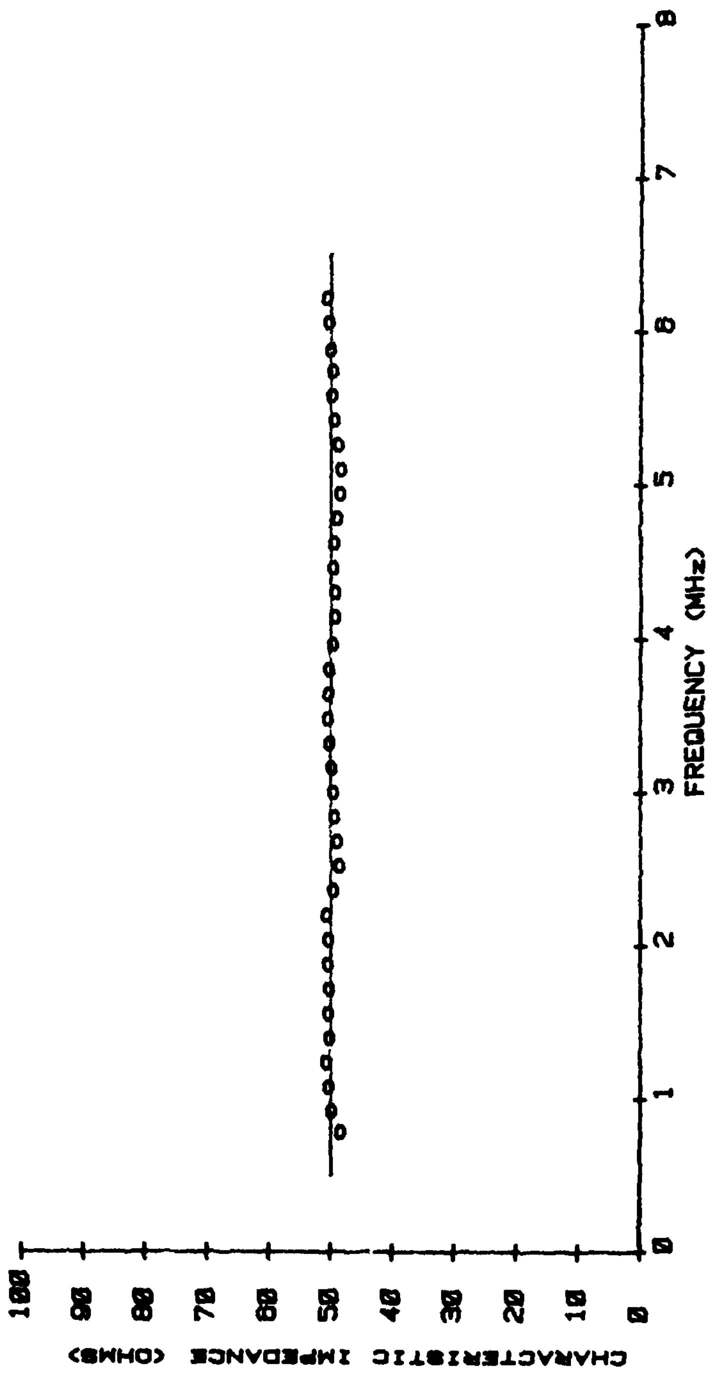


FIGURE 3. CHARACTERISTIC IMPEDANCE

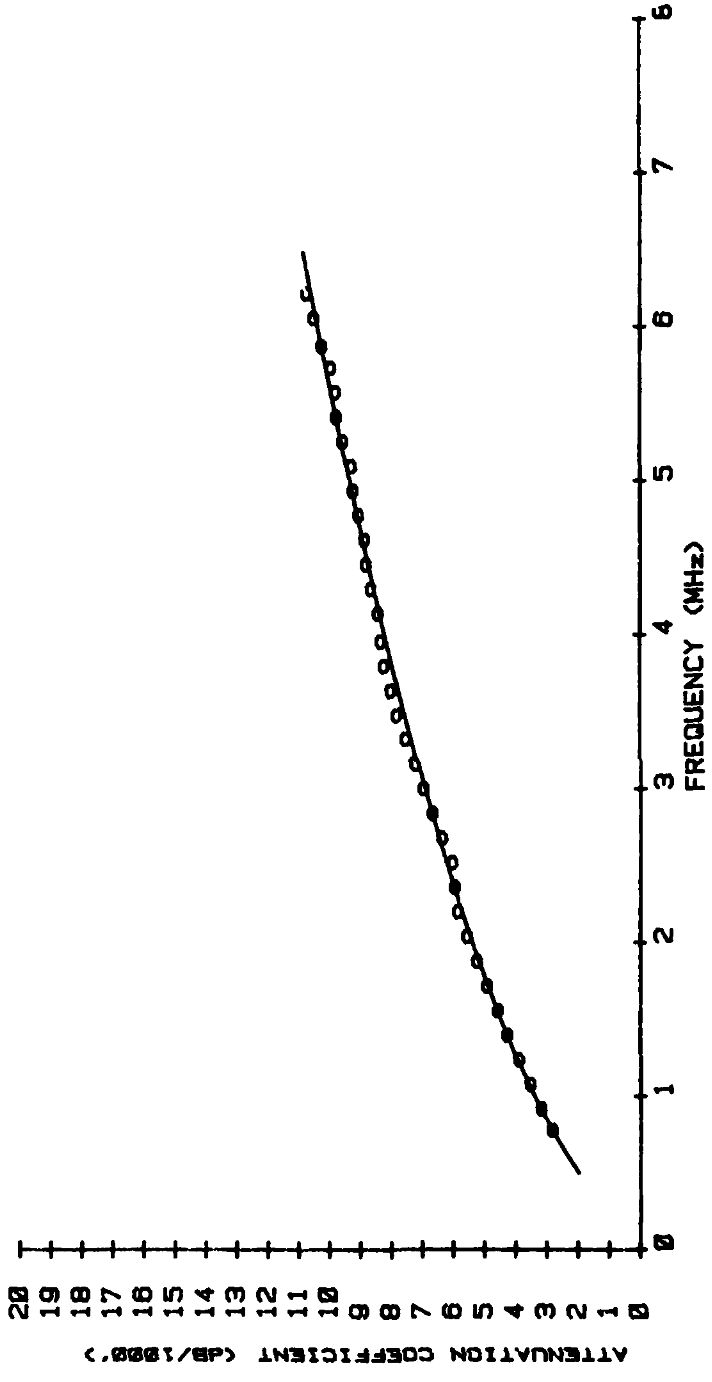


FIGURE 4. ATTENUATION COEFFICIENT

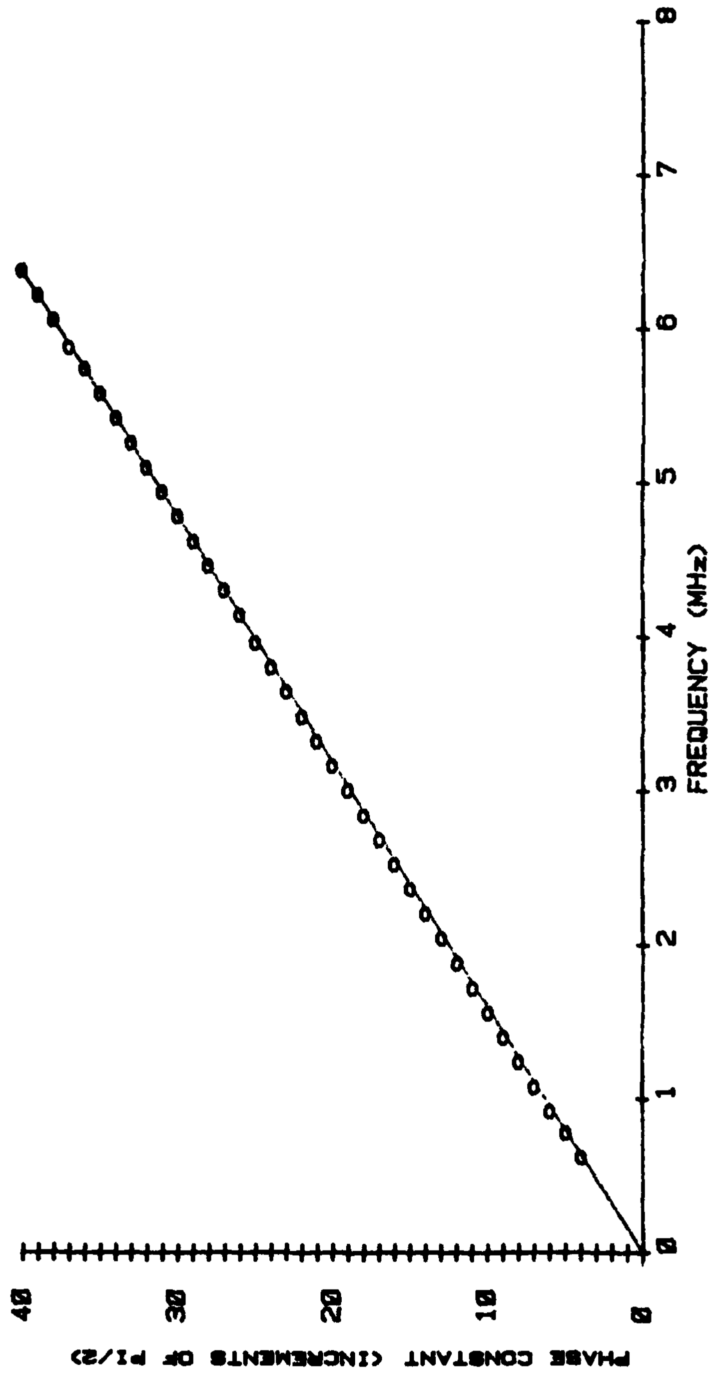


FIGURE 5. PHASE CONSTANT

And finally, the characteristic impedance Z_o has a small imaginary (reactive) component, but it is typically ignored. Measurements of $\measuredangle Z_{sc}$ were taken, and from these $\measuredangle Z_o$ was found to be only a few degrees.

LOAD PARAMETERS

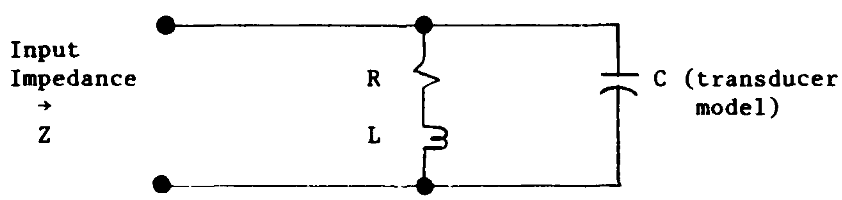
The ultrasonic transducer (the load) is primarily a capacitive device. Off-the-shelf pulser/receivers (ultrasonic instruments) are typically designed to excite this sort of load quite effectively. However, when the transducer is at the end of a long cable, instead of looking into an impedance of $1/j\omega C$ (a capacitor) the pulser/receiver looks into an impedance of

$$Z_o \coth \gamma \ell \left[\frac{Z_o \tanh \gamma \ell + \frac{1}{j\omega C}}{Z_o \coth \gamma \ell + \frac{1}{j\omega C}}\right] .$$

Figure 6 shows the capacitive characteristics of a transducer swamped by the presence of a long cable, and clearly indicates that remedial action is required. First, it would be desirable to terminate the cable in such a way as to prevent reflections from occurring since they show up at the receiver amplifier of the ultrasonic instrument and create problems. The following example shows one method of matching and its effect on input impedance.

First, the transducer's input impedance is measured and modeled (Figure 7). In this case, a 1/2-inch unfocused transducer with a 2.25 MHz center frequency is modeled well by a 1.0 nanofarad capacitor. Then, to make the load impedance 50 ohms (pure real) at 2.25 MHz, a series resistor-inductor combination is placed in parallel with it.

The objective is to make the network's input impedance, Z, equal to Z_o at 2.25 MHz. Using the model shown below the input impedance and appropriate values of components are calculated:



$$Z = [(R + j\omega L)(1/j\omega C)]/[R + j\omega L + (1/j\omega C)]$$

$$Z = (R + j\omega L)/[j\omega RC) + (1 - \omega^2 LC)] .$$

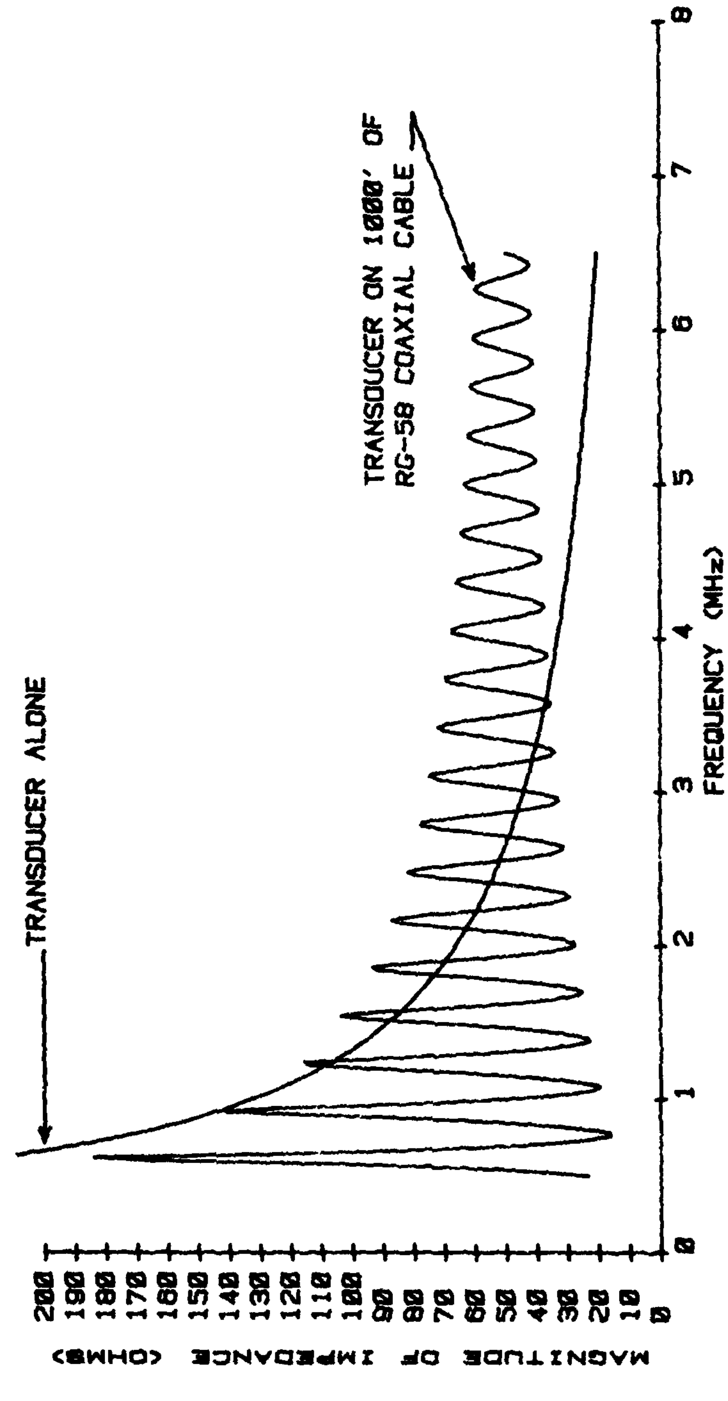


FIGURE 6. IMPEDANCE COMPARISON OF CABLE AND TRANSDUCER

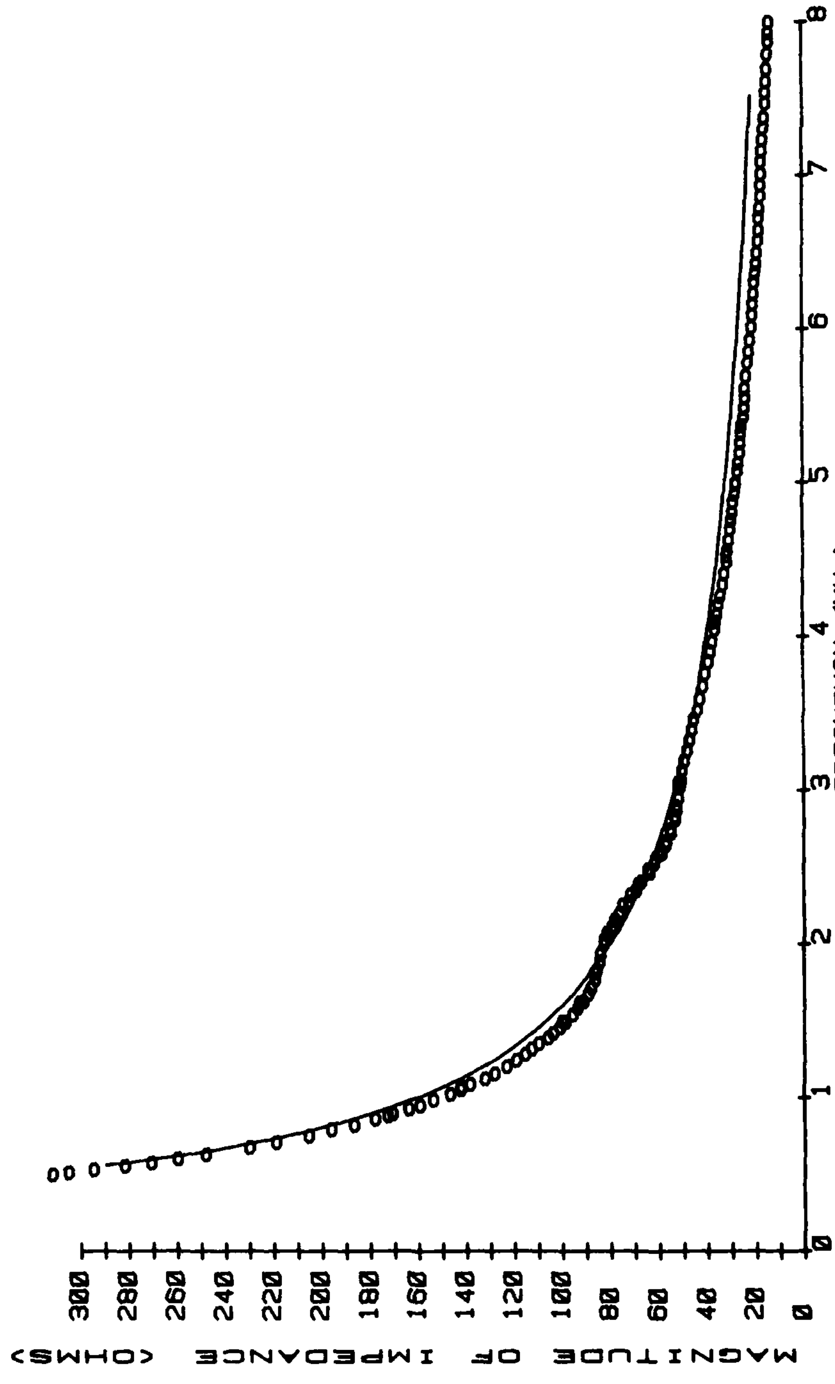


FIGURE 7. TRANSDUCER IMPEDANCE (MAGNITUDE)

Separating this into a real and imaginary part gives

$$Z = \frac{R}{(1-\omega^2LC)^2 + (\omega RC)^2} + j\omega C \frac{\frac{L}{C}(1 - \omega^2LC) - R^2}{(1-\omega^2LC)^2 + (\omega RC)^2} \quad .$$

For Z to equal $Z_o + j0$ (a pure real value),

$$0 = \frac{L}{C}(1-\omega^2LC) - R^2$$

from which $R = [\frac{L}{C}(1-\omega^2LC)]^{\frac{1}{2}}$.

Also, $Z = \frac{R}{(1-\omega^2LC)^2 + (\omega RC)^2}$ must be made to equal Z_o.

Substituting the expression for R and solving gives

$$L = Z_o^2\, C/(1 + Z_o^2\omega^2C^2)$$

and $R = Z_o\ /(1 + Z_o^2\omega^2C^2)$.

In the case we have chosen, where

$Z_o = 50\Omega$

$C = 1.0 \times 10^{-9}$ Farad

$\omega = 2\pi \times 2.25 \times 10^6$ Hz

we find $L = 1.667 \times 10^{-6}$ Henry

$R = 33.34\Omega$.

The impedance of this network as a function of frequency is shown in Figure 8, and its effect on the cable's input impedance is shown in Figure 9. Comparison of Figure 9 with the unmatched case (Figure 6) shows that a substantial improvement has been made.

The series R-L network in parallel with the transducer is not the only available configuration. In fact, limiting the choice to one resistor and one inductor allows three additional configurations:

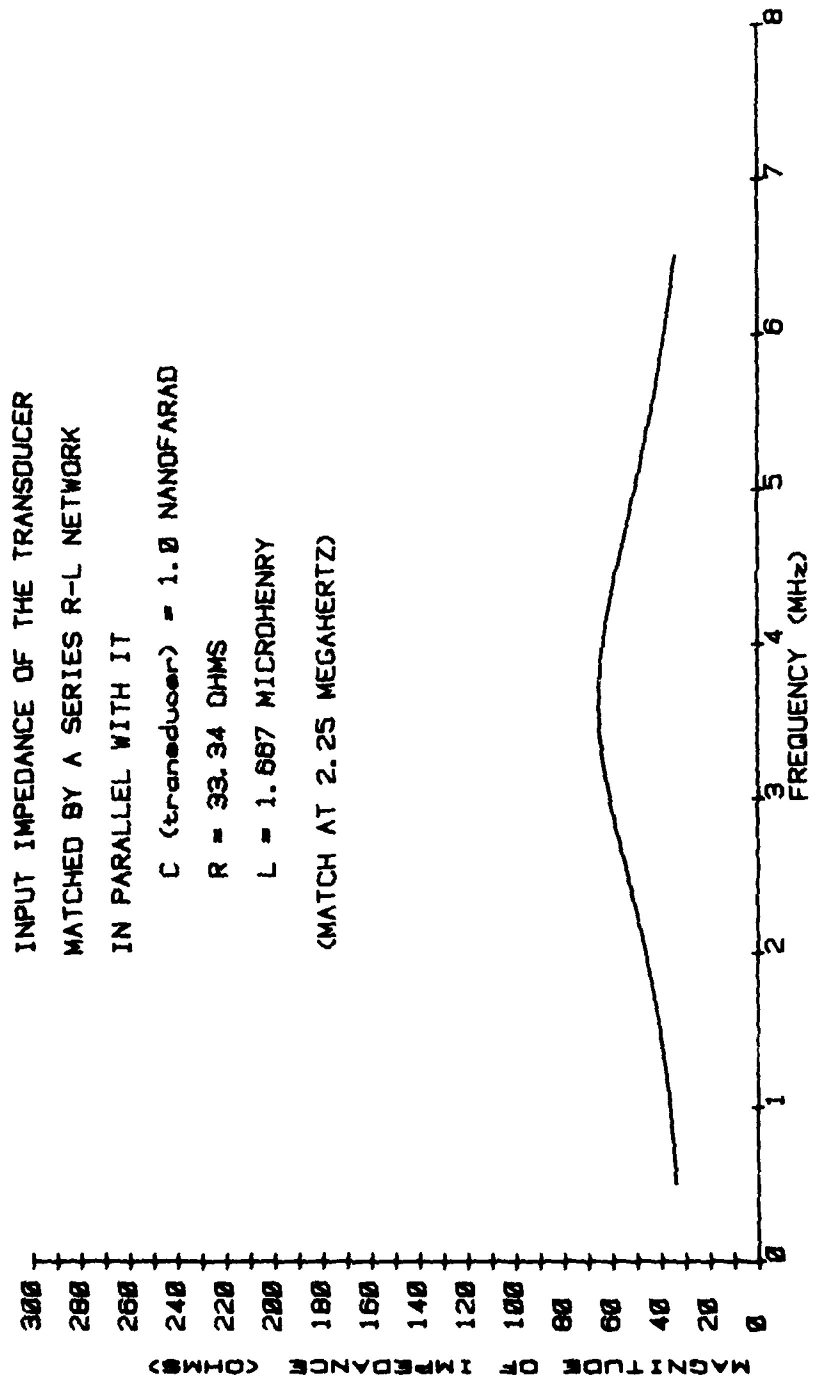


FIGURE 8. MATCHED TRANSDUCER IMPEDANCE

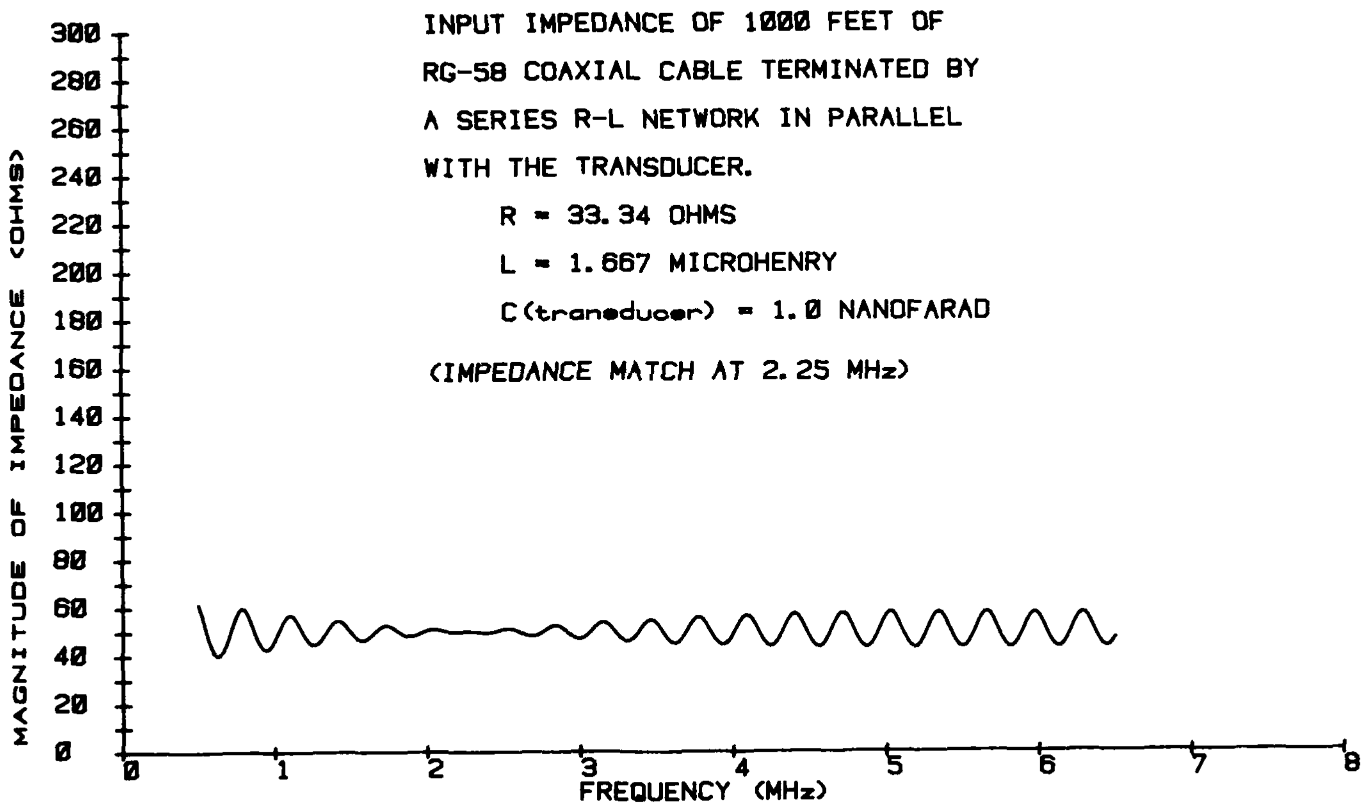
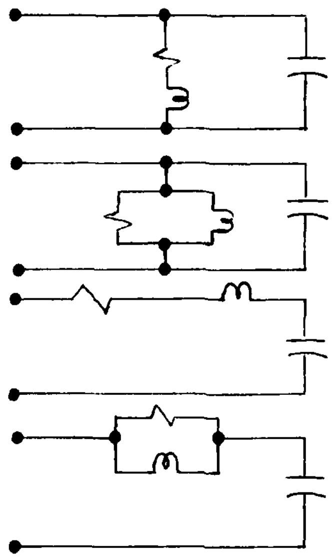


FIGURE 9. CABLE AND SERIES MATCHED TRANSDUCER IMPEDANCE



a) Series R-L in parallel with the transducer (already discussed)

b) Parallel R-L in parallel with the transducer

c) Series R-L in series with the transducer

d) Parallel R-L in series with the transducer

Options (c) and (d) have the unfortunate characteristic of reducing the voltage applied to the transducer and are therefore eliminated from consideration. Option (b) was studied since it allows full voltage to be applied to the transducer. Shown in Figure 10 are measured data and the theoretical curve for this configuration. This figure shows that at frequencies below 2.25 MHz the performance of this configuration is not as good as the series R-L network in parallel with the transducer (option (a)).

Other configurations which might perhaps utilize a wide-band transformer in the matching network have not been studied.

IMPLEMENTATION

Having found that a series R-L network in parallel with the transducer improves the transmission of pulses to the transducer, the next objective was to implement this network in hardware. Several approaches are possible, and one of these is described below. Since mechanical strength, small size, and waterproofed construction are desirable qualities it was decided to wind the inductor around the coaxial cable and pot the entire network in the standard NCSC cable termination which mates with the standard NCSC transducer housing. With no particular attempt to optimize the construction (by choosing a very fine wire size whose resistance and inductance would be correct without an additional resistor) a number 31 magnet wire was investigated and found to give approximately 1 microhenry per 20 turns around the coaxial cable (Figure 11). Thus, 33 turns in series with a 33 ohm resistor would form a suitable network. The steps used in building this are shown in Figure 12.

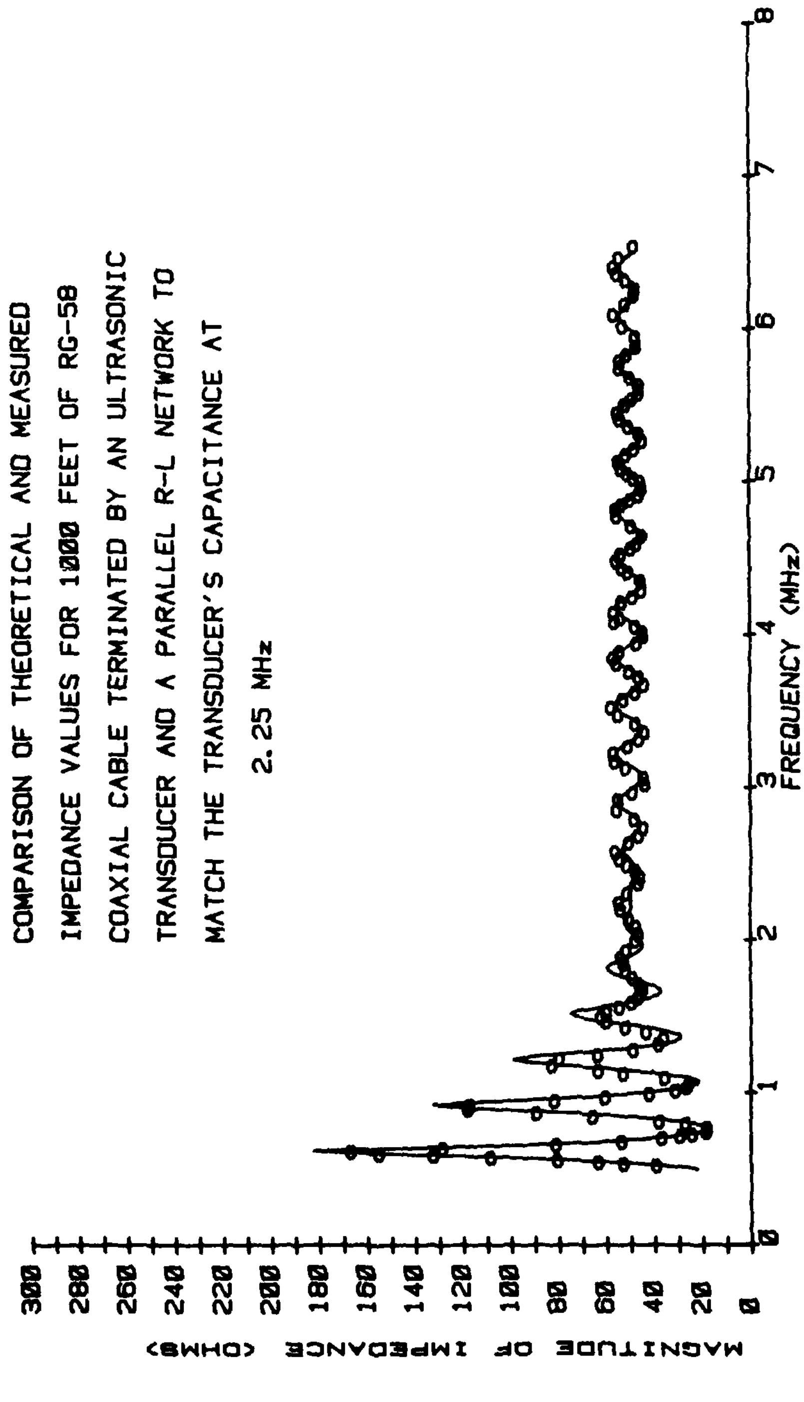


FIGURE 10. CABLE AND PARALLEL MATCHED TRANSDUCER IMPEDANCE

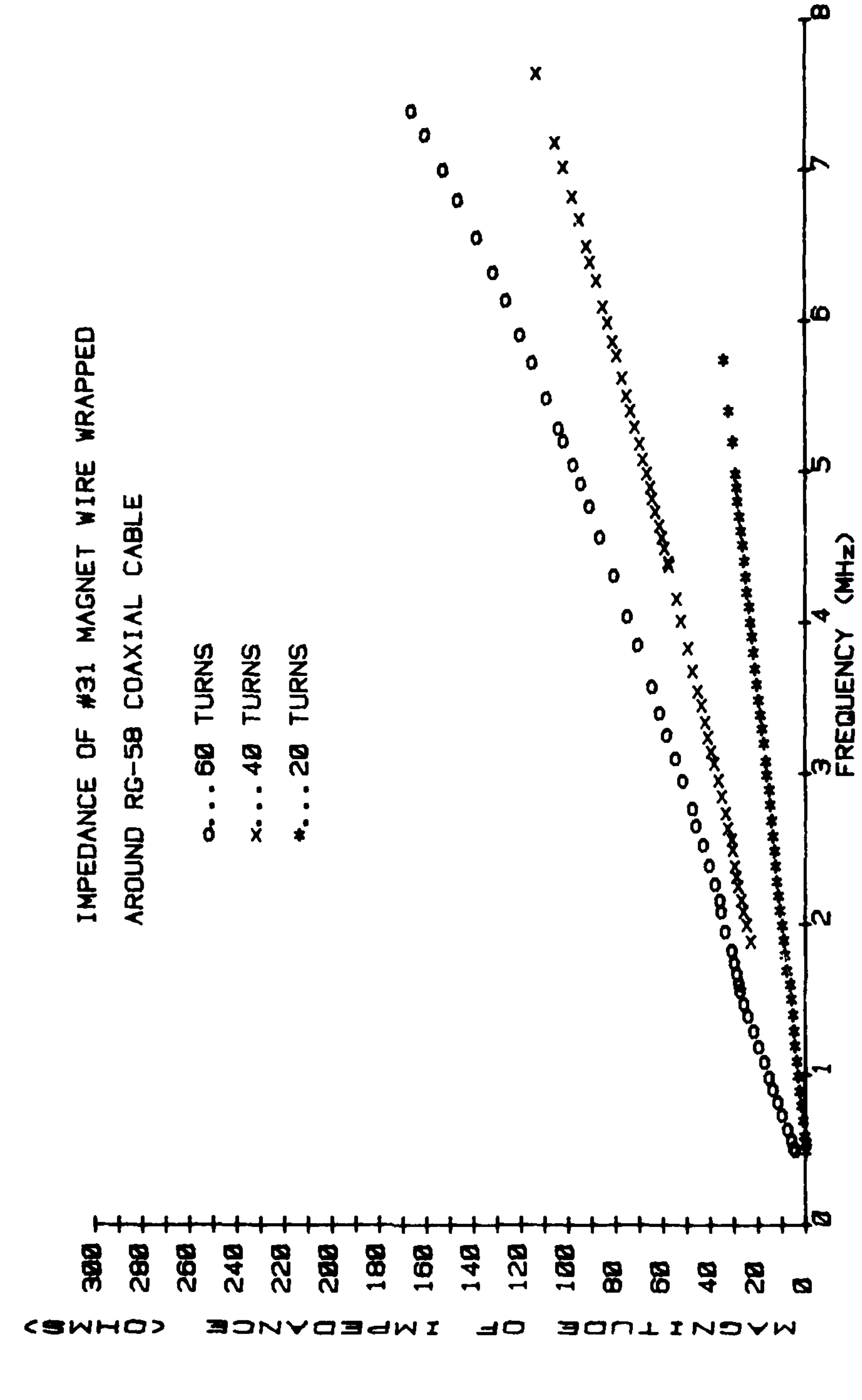


FIGURE 11. IMPEDANCE OF WIRE COILS

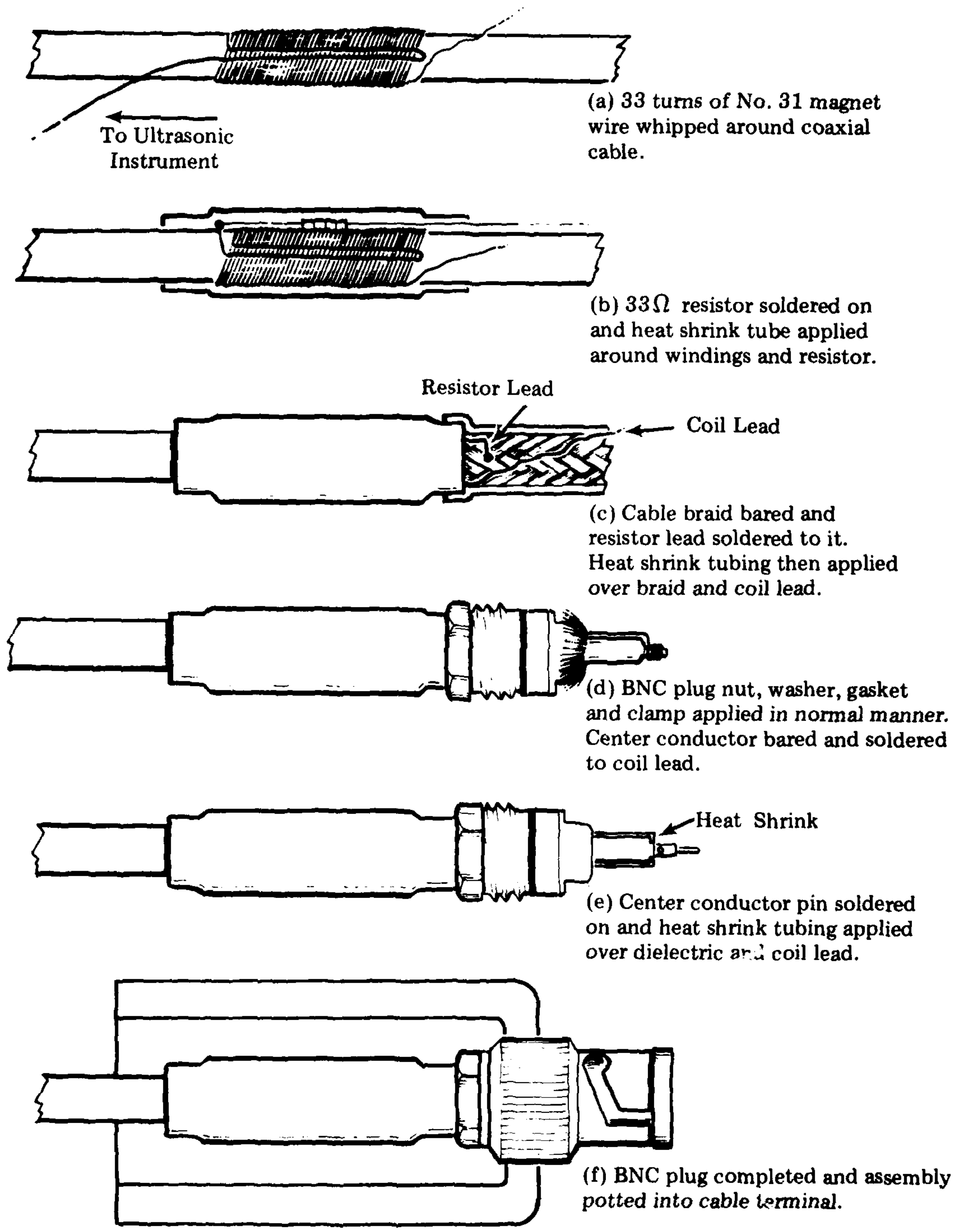


FIGURE 12. NETWORK CONSTRUCTION

The results of this construction applied to a 740-foot length of C-N-4 coaxial cable are shown in Figures 13a through 13d. It should be noted that C-N-4, like RG-58, has a characteristic impedance of 50Ω. C-N-4 differs from RG-58 primarily in its jacket which is an abrasion resistant non-hosing (water blocking) neoprene rather than plastic material. Electrically, the two cables are quite similar. Figures 13a and and 13c show conditions at the pulser and the transducer, respectively, for the cable before the matching network was connected. Evident in Figure 13a are a series of initial pulses rather than a single spike. The spacing between pulses indicates that 2.26 microseconds separate them. We calculate the time it would take an electromagnetic wavefront to travel 1480 feet of cable (round trip in a 740-foot length) as follows:

$$\tau = \frac{2\ell}{v} \approx \frac{2\ell}{(\frac{2}{3}c)}$$

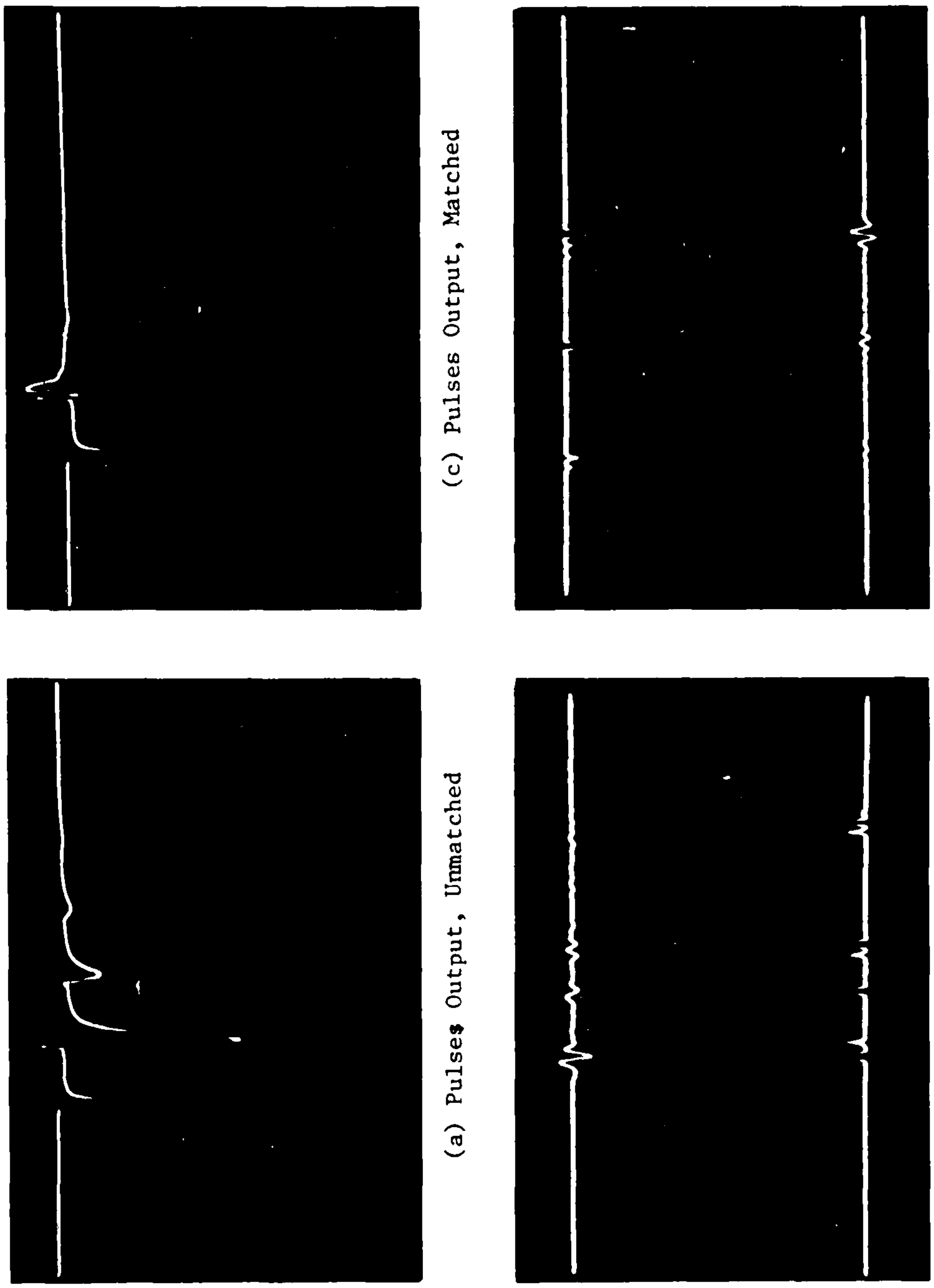
since the electromagnetic wave's propagation velocity in a cable filled with the dielectric used is about two-thirds the speed of light in a vacuum.

$$\tau \approx \frac{2 \times 740 \text{ feet}}{0.67 \times 3 \times 10^8 \frac{\text{m}}{\text{sec}}} \times \frac{\text{metre}}{3.28 \text{ feet}} = 2.25 \text{ microseconds}$$

This agreement with the time interval read off the oscilloscope screen helps confirm that reflections can and do occur. Their detrimental effect on the received waveform is shown in Figure 13b in which both the received waveform (upper) and the video presentation (lower) are shown. The first three spikes, from left to right on the video portion are the front surface echo, a spurious spike resulting from the reflection, and the first backwall echo from a 0.75-inch thick aluminum specimen. An ultrasonic inspector using this unmatched cable would have no way of determining the false indication from an internal defect or a thin area. Figures 13c and 13d show what occurs when the matching network is connected. First, the initial pulse is considerably cleaner and second, since the transducer is excited only once, the false indication disappears from the video presentation.

CONCLUSIONS

With suitable matching networks "off-the-shelf" NDT ultrasonic testing instrumentation can be operated with long (1000-foot) pulse generator-to-transducer cabling. This permits the instrumentation to be located topside where a UT technician can analyze the data in relative comfort. Also, with computer assistance the UT technician can analyze large amounts of data, edit it, and have it in report format shortly after the test is completed.



(a) Pulses Output, Unmatched

(c) Pulses Output, Matched

(b) Return Signals, Unmatched

(d) Return Signals, Matched

FIGURE 13. WAVEFORM COMPARISONS

Formulae developed in this paper for impedance matching of cables and transducers will be useful in matching problems occurring in other systems. Of particular interest is that terminating a cable in its characteristic impedance eliminates the dependence of input impedance on cable length. Thus, the same network will work on both long and short cables. Although the transducer's impedance affects network design, most commonly used ultrasonic transducers have a capacitance near 1000 picofarads; thus, relatively few different network designs can accommodate most common transducers.

RECOMMENDATIONS

It is recommended that all cables used for underwater ultrasonic testing be impedance matched during construction of the waterproofed electrical termination.

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843	Officer in Charge, Underwater Construction Team TWO, Naval Construction Battalion Center, Port Hueneme, CA 93043	93
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845	Officer in Charge, Fort Lauderdale Facility, Naval Surface Weapons Center, 1650 SW 39th St., Fort Lauderdale, FL 33315	97
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846	Oficer in Charge, Newport Laboratory, Naval Underwater Systems Center, Newport, RI 02840	99
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